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# GYROTRON RESEARCH AT THE ST. PETERSBURG STATE POLYTECHNICAL UNIVERSITY

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# ГИРОТРОННЫЕ ИССЛЕДОВАНИЯ В САНКТ-ПЕТЕРБУРГСКОМ ГОСУДАРСТВЕННОМ ПОЛИТЕХНИЧЕСКОМ УНИВЕРСИТЕТЕ

This paper presents the results of investigations performed by the researchers of the Department of Physical Electronics in the laboratory headed by Prof. F. Wagner and supported by the Ministry of Education and Science of the Russian Federation on the basis of MEGA-Grant. Methods for the improvement of helical electron beam quality and for enhancement of gyrotron efficiency, new gyrotron electron beam diagnostics are discussed.

GYROTRON, EFFICIENCY, HELICAL ELECTRON BEAM, DIAGNOSTICS, SAINT-PETERSBURG STATE POLYTECHNICAL UNIVERSITY, DEPARTAMENT OF PHYSICAL ELECTRONICS.

В статье представлены результаты исследований, выполненных сотрудниками кафедры физической электроники в рамках межфакультетской лаборатории, возглавляемой проф. Ф. Вагнером и поддерживаемой мегагрантом Министерства образования и науки Российской Федерации. Обсуждаются разработанные авторами методы повышения качества винтового электронного потока и эффективности работы гиротронов, а также новые методы диагностики электронных потоков в гиротронах.

ГИРОТРОН, ЭФФЕКТИВНОСТЬ, ВИНТОВОЙ ЭЛЕКТРОННЫЙ ПОТОК, ДИАГНОСТИКА, САНКТ-ПЕТЕРБУРГСКИЙ ГОСУДАРСТВЕННЫЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ, КАФЕДРА ФИЗИЧЕСКОЙ ЭЛЕКТРОНИКИ.

## I. Introduction

The principal step in the practical application of millimeter and submillimeter waves is connected with the discovery of the mechanism of coherent radiation of electron oscillators rotating in a constant magnetic field [1]. This mechanism underlies operation of devices named cyclotron-resonance masers (CRMs) or gyrodevices. Unique possibilities of gyrodevices allowed to achieve megawatt-level power in millimeter wavelength range and to obtain high power in submillimeter and terahertz ranges, which is much more than the power of conventional vacuum microwave devices, such as magnetrons, klystrons, travelling wave tubes and others. Gyrotrons became essential tools in controlled fusion experiments for the purposes of plasma heating and electron current drive. A high-power electron cyclotron system operating at 170 GHz planned for the ITER tokamak should be mentioned as an example of such application. This system consists of up to 26 gyrotrons. The specification for each gyrotron is to generate 1 MW or more during thousands of seconds. Gyrotrons are also used in material processing, particle acceleration, spectroscopy, radar systems, etc (see, e. g., [2, 3]).

In a gyrotron, the megawatt power level can be achieved on condition that its subsystems operate in a regime of extreme heat load. Therefore, the efficiency and limiting capabilities of the electron-optical system, the microwave cavity, the radiation output unit and the collector determine total efficiency and maximum achievable parameters of a gyrotron. Typically, the efficiency of high-power gyrotrons does not exceed 30 – 35 % without depressed collectors [4]. One of the basic problems of high-power gyrotrons is to form a high-quality helical electron beam (HEB). The «classical» electron-optical system of gyrodevices consists of the magnetron-injection gun (MIG) and the region of growing magnetic field where the transverse energy of electrons increases. This system is used for the formation of a hollow beam with small electron orbits in a wide range of gyrotron operation. In a well designed and aligned system, the main factor of beam quality deterioration is connected with the action of the self-field of electron space charge resulting partially from non-uniformities of electron emission and from the development of various types of parasitic space-charge instabilities [5]. One of them is the low-frequency instability developing in the cloud of electrons reflected from the magnetic mirror and accumulated in the trap between the cathode and the cavity. This instability should be avoided because the reflection of electrons from the mirror and the development of parasitic low-frequency oscillations (LFOs) in the trapped space charge are the main obstacles for gyrotron operation in high pitch factor regimes and for the achievement of high gyrotron efficiency.

An integrated theoretical and experimental study of low-frequency collective processes in gyrotron electron beams and of the effect of these processes on the operation of gyrodevices was performed at SPbSPU [5–12]. New understanding was obtained of the nature of LFOs, of the mechanisms of their excitation and their influence on the HEB characteristics. Methods for suppressing parasitic LFOs by optimizing the distributions of electric and magnetic fields were developed and studied experimentally in a 74.2 GHz, 100 kW gyrotron. The data on influence of cathode emission non-uniformities on the HEB characteristics allowed formulating the requirements for gyrotron cathodes needed for effective operation of high-power gyrotrons. Currently, the mentioned investigations continue in the frames of the laboratory headed by Prof. F. Wagner [13]. Our activity in the laboratory also concerns developing effective methods aimed at determination of the HEB characteristics in gyrotrons and at the development of cold field emitters for high-frequency gyrotrons. In this paper, we present the current status of gyrotron research in this laboratory.

## II. Improvement of the Electron Beam Quality and Enhancement of Gyrotron Efficiency

One of the developed methods for suppressing LFOs is based on the optimization of the electric field distribution in the MIG region [14]. This method was advanced by using a special control electrode insulated from the cathode unit. With this electrode it is possible to regulate the electric field distribution directly in an operating gyrotron.

### A. Trajectory Analysis of the MIG with a Control Electrode

In the simulations we have tested the electron-optical system of the SPbSPU gyrotron with the following operating-regime parameters: the accelerating voltage $U_0$ = 30 kV, the beam current $I_b$ = 10 A, the cavity magnetic field $B_0$ = 2.75 T, and the magnetic compression ratio $B_0/B_c$ = 18 ($B_c$ is the cathode magnetic field). A part of the cathode unit in the region above the emissive strip was replaced by a control electrode. The distribution of electric field in the gun was varied by regulating the voltage $U_{cont}$ between the control electrode and the cathode. The EGUN code was used in the 2D simulation procedure.

The key parameter determining intensity of parasitic LFOs is the coefficient of electron reflection from the magnetic mirror that can be changed by varying the pitch factor α, the transverse velocity spread $\delta v_\perp$, and the shape of the velocity distribution function $F(v_\perp)$ [10]. For fixed values of $U_0$, $I_b$, $B_0$, $B_0/B_c$, the increase of voltage $U_{cont}$ in the range from −12 to +5 kV, as resulted from the simulations, causes an increase of both α and $\delta v_\perp$. Fig. 1 shows the

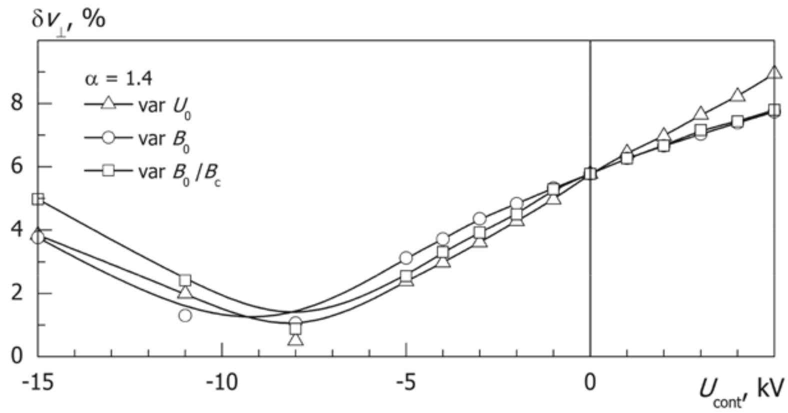


Fig. 1. Transverse velocity spread $\delta v_\perp$ (rms-value) as a function of control electrode voltage $U_{cont}$ for the pitch factor maintaining at $\alpha = 1.4$ by the adjustment of voltage $U_0$, magnetic field $B_0$, and compression ratio $B_0/B_c$

dependencies $\delta v_\perp(U_{cont})$ calculated for the pitch-factor $\alpha = 1.4$. This value of $\alpha$ was maintained by varying one of the parameters $U_0$, $B_0$ or $B_0/B_c$. As follows from Fig. 1, the optimization of the electric field distribution by regulating the control electrode voltage allows to improve electron beam quality due to the reduction of the velocity spread component induced by dc space charge in the MIG region. Applying the optimal negative voltage to the control electrode can provide regimes of gyrotron operation with high pitch factors and without parasitic LFOs, which are promising for the achievement of high gyrotron efficiency.

### B. Experiments on Suppression of LFOs in the Gyrotron with a Multi-Sectional Control Electrode

The measurements were made in the SPbSPU gyrotron equipped with a set of diagnostic tools for determining the HEB characteristics, specifically the distributions of emission current density on the cathode surface, electron energy spectra in the collector region, and characteristics of low-frequency dynamic processes in the electron space charge [10]. The MIG design discussed above was implemented in this tube. In the experimental version, the control electrode consists of four sections shifted one from another in azimuthal direction (Fig. 2). These sections are electrically isolated. Therefore, it is possible to regulate the electric field distribution in the gun region by varying the potentials of these sections.

The intensity of parasitic LFOs was measured at the operating values of the working parameters $U_0$, $I_b$, $B_0$, $B_0/B_c$ and at different values of the potentials of the control electrode

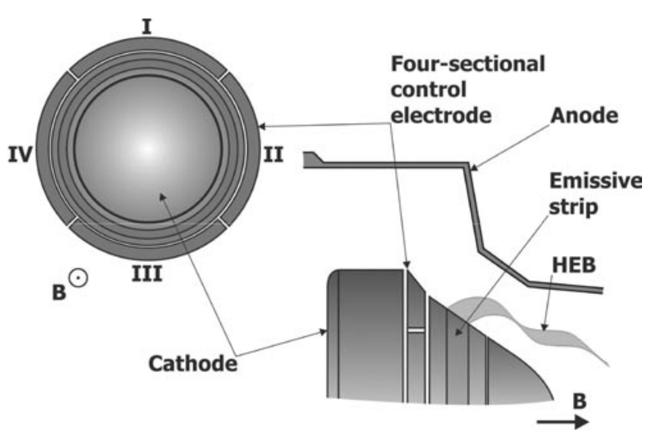


Fig. 2. Schematic drawing of the SPbSPU gyrotron gun region

sections. In the case of connected sections, the electric field distribution is azimuthally quasi-uniform. For this scheme we observed the growth of the oscillation intensity with increasing control voltage, which can be generally explained by increasing both the pitch factor and the velocity spread (see the data of the simulations). Additional suppression of LFOs (in comparison with the scheme of connected sections) was achieved when the azimuthal distribution of electric field correlated with the azimuthal distribution of the cathode emission current density $j_e(\theta)$. The distribution $j_e(\theta)$ for the studied emitter was similar to the distributions described in [10] and was characterized by reduced emission from the cathode area equal to approximately a quarter of the circumference of the emissive strip. This reduced emission was caused by an inhomogeneity in the heating of the emitter due to a gap in the cathode heater winding. The reduction of the emission current density results in a decrease of potential depression owing to the electron space charge and in an increase of the pitch factor and reflection from the mirror for the electrons emitted from this area. Section I of the control electrode (see Fig. 2) was located near the cathode area with reduced emission. As an example, we can indicate the following regime providing the high quality HEB: the cathode potential $\varphi_c = -30$ kV, the potential of Section I $\varphi_{\mathrm{I}} = -29$ kV, the potential of the other sections $\varphi_{\mathrm{II\text{-}IV}} = -26$ kV. For this regime the LFOs amplitude was the same as for the initial regime without control voltage ($\varphi_{\mathrm{I\text{-}IV}} = \varphi_c$). However, the calculated pitch factor was higher ($\alpha = 1.5$ and 1.4, respectively). Improvement of the HEB quality is thought to be the result of the decrease of the velocity spread caused by the cathode emission non-uniformity. Additionally, the mechanism of LFOs suppression due to the losses of the trapped electrons by their interception with the control electrode can also play a role [14].

### C. Experiments on the Enhancement of Gyrotron Efficiency

In the next experiments the influence of potentials of the control sections on gyrotron output power and efficiency was studied. The measurements were made with a $LaB_6$ cathode being characterized byrelatively high emission uniformity (emission spread $\delta j_e < 25$ %). For this cathode the maximum value of gyrotron efficiency at the main $TE_{12,3}$ mode was about 42 % in the absence of any control voltage. Such a high efficiency was caused by suppression of the parasitic LFOs due to the optimization of the electric and magnetic field distributions [11]. Controlling the electric field distribution with the control electrode allowed to obtain further enhancement of the gyrotron efficiency. Fig. 3 shows the dependencies of the efficiency $\eta$ on the cavity magnetic field $B_0$ in the zone of the $TE_{12,3}$ mode for the control voltages $U_{cont} = 0$ and−5 kV (the scheme of connected control sections). The regime with $U_{cont} = -5$ kV was characterized by reduced LFOs amplitude, which allowed to increase the average pitch factor in HEB by increasing the compression ratio. This resulted in an enhancement of the efficiency. The maximum achievable value of $\eta$ is equal to

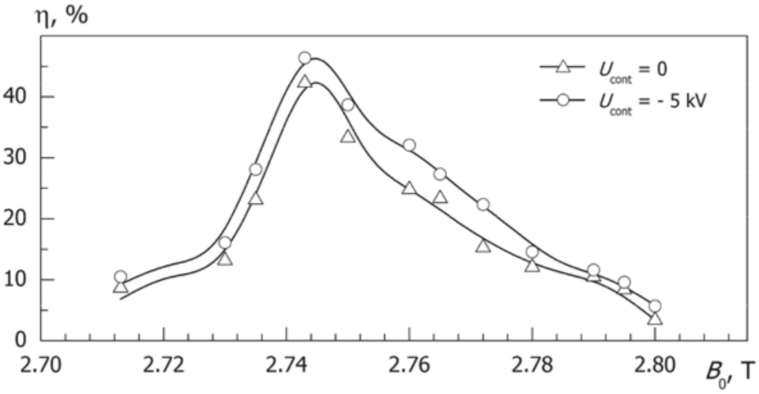


Fig. 3. Efficiency $\eta$ at the main $TE_{12,3}$ mode as a function of magnetic field $B_0$ for different control electrode voltage $U_{cont}$ ($U_0 = 30$ kV, $I_b = 9$ A, $B_0/B_c = 18.35$)

~ 46 % (see Fig. 3). At present, the experiments on the enhancement of the gyrotron efficiency by the optimization of the electric field distribution are in progress.

## III. Diagnostics of Helical Electron Beam in Gyrotrons

### A. X-Ray Diagnostics

Bremsstrahlung X-rays produce at the collector can be used for the definition of electron energy distributions in gyrotrons and other microwave devices with high-energy electron beams. Knowledge of the energy distributions in electron beams can be helpful in the solution of various practical problems, e. g. for benchmarking computer codes, for the control of beam adjustment accuracy (if spatially resolved data on electron spectra are available), for the development of depressed collector systems, and so on. The diagnostic technique is based on processing X-ray spectra measured with a spectrometer placed outside the gyrotron [15, 16]. This method is relatively inexpensive in realization and non-disturbing.

Successful proof-of-principle experiments were performed at the Karlsruhe Institute of Technology (Germany) with the 2 MW, 170 GHz coaxial cavity short-pulse (< 10 ms) pre-prototype ITER gyrotron and with the 1 MW multi-frequency (100–140 GHz) tunable gyrotron for the ASDEX Upgrade ECH system. In the multi-frequency gyrotron, the X-ray spectrometer was placed beyond the 2-mm-thick aluminum window and collected photons elastically scattered in the aluminum layer. This layout allowed us to obtain spectra of bremsstrahlung X-rays averaged over the complete collector surface.

Then the gyrotron was operated in a low-current regime without any significant rf fields, and all electrons reached the collector with the same energy corresponding to the accelerating voltage, the measured X-ray spectra were in very good agreement with basic theory, i. e. with Kramers' law and exponential attenuation of low-energy photons in aluminum (Fig. 4). This confirmed the correct performance of the technique and the equipment in use.

In the regimes of normal gyrotron operation electron energy was partially spent for mm-wave pumping and the measured bremsstrahlung spectra were different. Fig. 5, *a* shows a typical X-ray spectrum measured in the presence of MW-level output power at the voltage of 85 kV, the beam current of 45 A, and the output power of 750 kW. The dashed lines given for comparison represent analytical approximations of the X-ray spectra measured in low-current regimes at $U$ = 62 kV and 87 kV. The electron energy distribution reconstructed from the X-ray spectrum is shown in Fig. 5, *b*. We collected the electron energy spectra for different regimes of the multi-frequency gyrotron, which yielded helpful information about its performance.

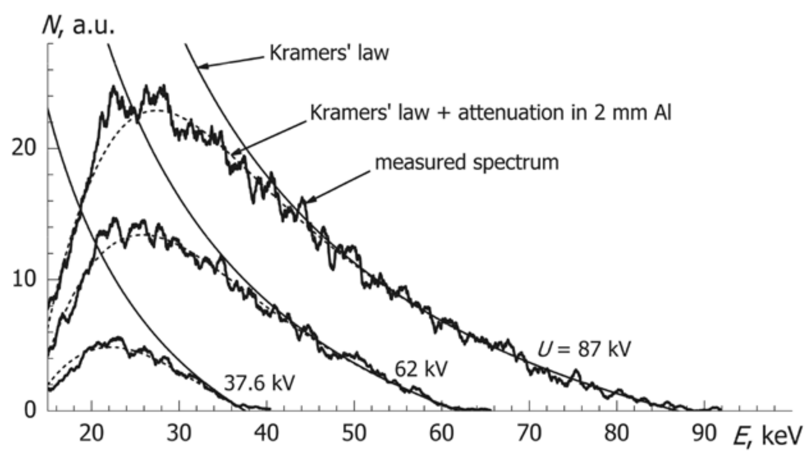


Fig. 4. Bremsstrahlung spectra $N(E)$ measured in low-current regimes without rf oscillations at different accelerating voltages $U$.
Good agreement of the measured spectra with basic theory (dash lines) confirms the consistency of the data

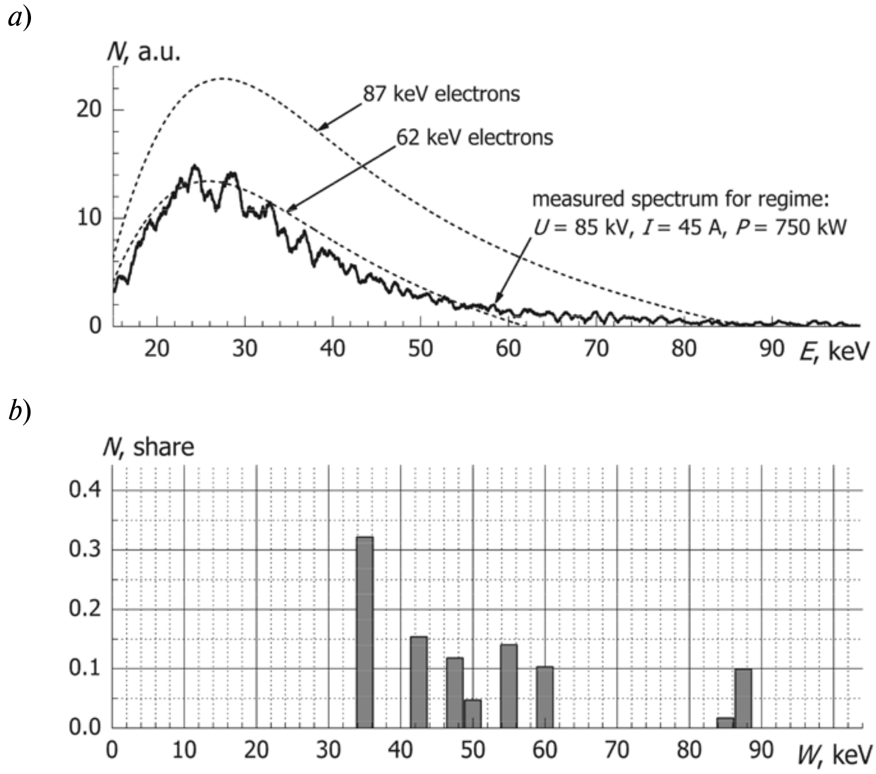


Fig. 5. X-ray spectrum $N(E)$ measured in the presence of mm-wave oscillations and basic functions (analytical approximation of measured spectrum) for 62 keV and 87 keV electrons (*a*). Electron energy distribution $N(W)$ calculated from the given measured X-ray spectrum (*b*)

The performed testing experiments confirmed that the bremsstrahlung-based diagnostics of energy distributions in electron beams can be successfully applied to high-power gyrotrons. Experience from these experiments can be used for adaptation of this diagnostics to the geometry and operating regimes of a particular gyrotron.

### B. Microwave Diagnostics

Another diagnostic method is aimed at the determination of electron velocities in the region before HEB entering the microwave cavity. Data on average pitch factor and velocity spread in this region are very important for the determination of the efficiency of the energy transformation from electrons to the rf field in the cavity. Analytical and numerical calculations show the possibility to obtain information about the axial velocity distribution of electrons on the base of frequency dependencies of the gain of a GHz signal propagating in a special slow-wave structure located in the beam formation region. The slow-wave structure in the form of a diaphragmatic waveguide (Fig. 6) was designed to implement this diagnostics for the determination of electron velocities in the SPbSPU gyrotron. The set of calculated de-

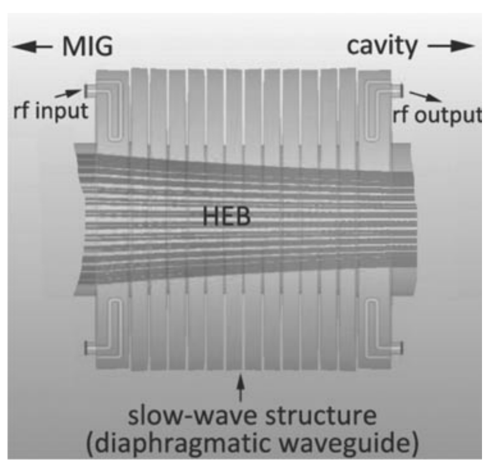


Fig. 6. Schematic drawing of the beam formation region between the gun and the cavity with the slow-wave structure

pendencies of gain on frequency varying in the range 5 – 6 GHz were obtained for different HEB parameters of this gyrotron. The data of the numerical simulations will be used as basis for processing corresponding dependencies in future experiments.

## IV. Conclusion

The gyrotron research performed at SPbSPU is aimed at the enhancement of gyrotron efficiency and the development of new methods for helical electron beam diagnostics. The acquired knowledge and developed technical solutions can be used for the next generation of effective high-power gyrotrons, used in controlled fusion experiments. The following investigations are planned in the continuation of the performed gyrotron research as reported in this paper:

1. Development of methods for effective recuperation of electron energy in gyrotrons with depressed collector. Study of the possibility to achieve enhanced gyrotron efficiency resulting from both improvement of HEB quality and energy recovery in the collector region.
2. Application of new diagnostic methods for the investigation of electron energy spectra in the working regimes of high-power gyrotrons using X-ray diagnostics, and for the determination of velocity characteristics of electrons in the SPbSPU gyrotron using microwave diagnostics.

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